REMARKS/ARGUMENTS

Claims 1-16 were pending in the present application. The present response does not amend, cancel, or add any claims, leaving pending in the application claims 1-16. Reconsideration of the rejected claims is respectfully requested.

I. Rejection under 35 U.S.C. §112

Claims 1-16 are rejected under 35 U.S.C. §112, first paragraph, as failing to comply with the enablement requirement. Particularly, the Office Action states that applicant does not detail what kind of light the detector detects, and it is not know what type of light source or detector is being used (OA pp. 4-5).

The scope of enablement "is that which is disclosed in the specification plus the scope of what would be known to one of ordinary skill in the art without undue experimentation *National Recovery Techs., Inc. v. Magnetic Separation Sys., Inc., 166 F.3d 1190, 1195-96 (Fed. Cir. 1999).* MPEP §2164.04 states that an Examiner should find a specification to be non-enabling when:

> the specification fails to teach how to make and use the claimed invention **without undue experimentation**, or that the scope of any enablement **provided to one skilled in the art** is not commensurate with the scope of protection sought by the claims. This can be done by making specific findings of fact, supported by the evidence, and then drawing conclusions based on these findings of fact. For example, doubt may arise about enablement because information is missing about one or more essential parts or relationships between parts **which one skilled in the art could not develop without undue experimentation**. In such a case, the examiner should specifically identify what information is missing and why one skilled in the art could not supply the information without undue experimentation.

(*emphasis added*). Applicants respectfully submit that subject matter recited in claims 1-16 is disclosed in the specification with sufficient detail that one of ordinary skill in the art at the time the application was filed could make or used the invention recited in each claim without undue experimentation.

In the background section of the application as filed, it is stated that "Optical scatterometry, reflectometry, or ellipsometry methods can be used to measure grating profile shapes and critical dimensions" (p. 8, lines 22-24). As stated in the title of the application, the optimized aperture can be used with these methods for "optical CD/profile metrology," where

CD refers to a critical dimension as known in the art It is also stated that, as an example, Fig. 1 illustrates a "reflectometer-type measurement instrument" that can be used for grating measurement" (p. 1, lines 33-35). This "reflectometer-type instrument utilizes "illumination from a source" that is focused onto the grating, whereby "reflected radiation" is diverted toward a "radiation-sensing detector" whereby reflectivity data can be acquired "over a range of wavelengths" (p. 1, line 33-p. 2, line 4). Applicants respectfully submit that illumination sources and optical detectors used in reflectometer-type instruments such as scatterometers, reflectometers, and ellipsometers to measure critical dimension and line width would have been known to one of ordinary skill in the art at the time the subject matter of the present application was invented, such that the disclosure is sufficiently enabling.

As an example of the state of the art at or around the time the present application was filed, Applicants have attached hereto the following four references:

(1) <u>U.S. Patent 5,867,276 – issued Feb. 2, 1999</u>: This patent relates to "optical scatterometry," which can be used to examine "a sample having [a] periodic structure" (Abstract; col. 2, lines 52-61). The reference states at col. 4, lines 4-13 (when characterizing the prior art):

> Typically, continuous, low power lasers such as HE-Ne, Ar-ion, He-Cd and semiconductor diodes are used for the source of the light beam, although other sources of radiation might be used equally well in the scatterometer arrangement described here. The wavelength of the sources might range from x-ray through the visible and microwave regions, to the long wavelength region which corresponds to frequencies of just a few Hz. Generally, larger wavelengths provide for characterizing samples that have structure of larger dimensions.

The reference also states at col. 5, lines 22-31 (when discussing the preferred broadband embodiments):

> Representative light sources include commonly available incandescent (e.g., tungsten filament), high pressure Xe, and halogen lamps. This type of source is to be contrasted with lasers and low pressure discharge lamps which have output at one or more wavelengths that extend over a relatively narrow wavelength range. Alternatively, the source (105) might comprise multiple wavelengths from one or more lasers or light emitting diodes which, collectively, provide a source (105) that has a broad spectral composition.

Further, at col. 5, lines 40-43, it is stated that the detector/spectrometer "might comprise any instrument that contains one or more dispersive optical elements which is capable of providing

spectrally-resolved information concerning the diffracted beam" from a source as described above.

(2) U.S. Patent 5,963,329 – issued Oct. 5, 1999: This patent relates to a method for nondestructively determining the line profile or topographical cross-section of repeating lines on a substrate by collecting, measuring, and recording reflected radiation as a function of wavelength (Abstract). These determinations can be used to ensure that "critical dimensions, line profiles, and feature depths are under control (col. 1, lines 17-21). Figure 9 shows an example of an apparatus that can be used for such a determination, which includes a broad-band light source and detector. It is stated in the background section that it is known to use scatterometry to characterize periodic topographic structures using a light beam from a light source that could be a laser (col. 2, lines 7-17) or a broadband source (col. 7, line 63). It is also stated that detectors for measuring the reflected light "are well known in the art" (col. 8, lines 15-20).

(3) Specular Spectral Profilometry on Metal Layers, Junwei Bao et al., Proceedings of SPIE Vol. 3998 (2000): This 2000 reference discusses using a specular spectroscopic profilometer (scatterometry) to extract a CD (critical dimension) profile (p. 884). In the background section, it is mentioned that "an automated He-Ne laser spectrometer" had previously been used to measure critical dimensions of patterned features (p. 883). The reference specifically refers to a "KLA–Tencor ellipsometer" that can be used to measure the response from the gratings (p. 888). Further, the reference states on page 884 that "conventional spectroscopic ellipsometry and reflectometry equipment can be used." This is evidence that such sources and detectors were well known, even "conventional," by the year 2000, and were commercially available before the filing of the present invention.

(4) Manufacturing Considerations for Implementation of Scatterometry for Process Monitoring, John Allgair et al., Proceedings of SPIE Vol. 3998 (2000): This 2000 reference discusses using spectroscopic scatterometry to detect and quantify measurements such as CD (critical dimension) measurements (p. 125). Figure 1 shows an illustration of scatterometry fundamentals that can be used to measure a grating. Again, by the year 2000, the systems and

methods for making scatterometry measurements were well known to the point that the reference did not even need to describe the apparatus in order for the paper to be understood. Further, there are a number of references relating to scatterometry systems cited in the paper that go as far back as 1992, all references pre-dating the filing of the present application.

As can be seen from these references, illumination sources and optical detectors used in reflectometer-type instruments such as scatterometers, reflectometers, and ellipsometers to measure critical dimension and line width would have been known to one of ordinary skill in the art at the time the present application was filed. Advantages of an optimized aperture shape as described and claimed in the present application could be obtained for any of the above-described systems, and could be implemented in any of the above systems in light of the present specification without any undue experimentation. It is therefore respectfully submitted that the claims 1-16 are sufficiently enabled. Applicants therefore respectfully request that the rejection with respect to claims 1-16 be withdrawn.

II. Conclusion

In view of the above, it is respectfully submitted that the application is now in condition for allowance. Reconsideration of the pending claims and a notice of allowance is respectfully requested.

The Commissioner is hereby authorized to charge any deficiency in the fees filed, asserted to be filed, or which should have been filed herewith (or with any paper hereafter filed in this application by this firm) to our Deposit Account No. 50-1703, under Order No. TWI-31500. **A duplicate copy of the transmittal cover sheet attached to this Response to Office Action Mailed July 7, 2004, is provided herewith.**

Respectfully submitted,

STALLMAN & POLLOCK LLP

Dated: August 30, 2004

By: Jason D. Lohr
Reg. No. 48,163
Attorneys for Applicant(s)

Atty Docket No.: TWI-31500

Manufacturing Considerations for Implementation of Scatterometry for Process Monitoring

John Allgair, Dave Benoit, Rob Hershey, Lloyd C. Litt
Motorola APRDL, Austin, TX 78721

Ibrahim Abdulhalim, Bill Braymer, Michael Faeyrman, John C. Robinson, Umar Whitney, Yiping Xu, Piotr Zalicki, Joel Seligson
KLA-Tencor Corporation, San Jose, CA 95134

ABSTRACT

The continuing demand for higher frequency microprocessors and larger memory arrays has led to decreasing device dimensions and smaller process control windows. Decreasing process control windows have created a need for higher precision metrology to maintain an acceptable precision to tolerance ratio with a reasonable sampling rate. In order to determine and reduce across chip, across wafer, and across lot linewidth variations, higher sampling is required which, in turn, demands faster move acquire measure (MAM) times to maintain throughput. Finally, the need to detect and quantify sidewall angle changes in addition to CD measurements is becoming critical. Spectroscopic Scatterometry is a metrology technique which offers the potential to meet these requirements. This work explores some of the fundamental technology concerns for implementing scatterometry in a manufacturing environment. These concerns include mark requirements and characterization necessary for library generation. Comparison of scatterometry data to in-line CD SEM, x-section SEM, and AFM results will be presented.

Keywords: Scatterometry, spectroscopic scatterometry, optical reflectometry, optical microscopy, process control, Critical Dimension Metrology and optical CD.

1. Introduction

The continuing demand for higher frequency microprocessors and larger memory arrays has led to decreasing device dimensions in general accordance to Moore's law. Shrinking gate sizes have led to reduced process control windows that drive a need for higher precision metrology to maintain an acceptable precision to tolerance ratio with a reasonable sampling rate. According to the 1998 International Technology Roadmap for Semiconductors, three-sigma metrology of one nanometer will be needed for the 70 nm node in 2008. As with past roadmaps, the industry will likely achieve this node well before 2008.

Increased sampling can be applied to increase the metrology precision and achieve an acceptable precision to tolerance ratio in manufacturing. In order to determine and reduce across chip, across wafer, and across lot linewidth variations, higher sampling is required which, in turn, demands faster MAM times to maintain throughput. Also, in order to achieve wafer-to-wafer and die-to-die control, higher precision single point metrology, that lends itself easily to integration, is required.

Current linewidth process control methodologies use a critical dimension measurement, typically obtained from a CD SEM. This measurement gives limited indication as to the sidewall angle or height of the feature. As transistor gate lengths decrease, the effects of non-vertical gate profiles will have an increased contribution to transistor performance characteristics. The need to detect and quantify sidewall angle changes in addition to CD measurements is becoming critical.

Optical metrology techniques, generally known as scatterometry, offer the potential to meet these requirements. A variety of work has been published since the early 1990's illustrating the potential for scatterometry for semiconductor process control [1-5]. Three-sigma precision of 1.53 nm has been achieved for patterned resist on a polysilicon gate stack. The capability to predict sidewall angle and determine properties of underlying films has also been demonstrated. This work explores some of the fundamental technology concerns for implementing scatterometry in a manufacturing environment. These concerns

include the types of equipment available, predictive capability, mark requirements, and characterization necessary for library generation.

2. Fundamentals of Scatterometry

The principle of scatterometry is explained with the help of Figure 1. The physical structure consists of a flat substrate, and possibly a multilayer thin film coating, with a line grating on it. A collimated beam of light is directed onto the grating, with the width of the beam sufficiently large to cover at least several tens of periods of the grating. Depending on the period of the grating, Γ, and the wavelength of the incident light, λ, there may be a number of diffracted orders reflected from the grating. The 0^{th} order is defined by the specular reflection of light, satisfying the equality $\Theta_{out} = \Theta_{in}$, where Θ_{out} and Θ_{in} are the angles of the reflected and incident beams with respect to normal. Denoting the incident light intensity by I_{in}, and the reflected light intensity by I_{out}, the reflectance, R, may be defined as:

$$R = I_{out}/I_{in}.$$

The reflectance R depends on the physical target structure as well as on the properties of the incident light beam. Physical target structure parameters which affect the reflectance include grating period, grating line geometry, grating refractive index, multi-layer thin-film coating, and base substrate. Properties affecting the incident light beam reflectance include wavelength, angle of incidence, polarization, and azimuth angle.

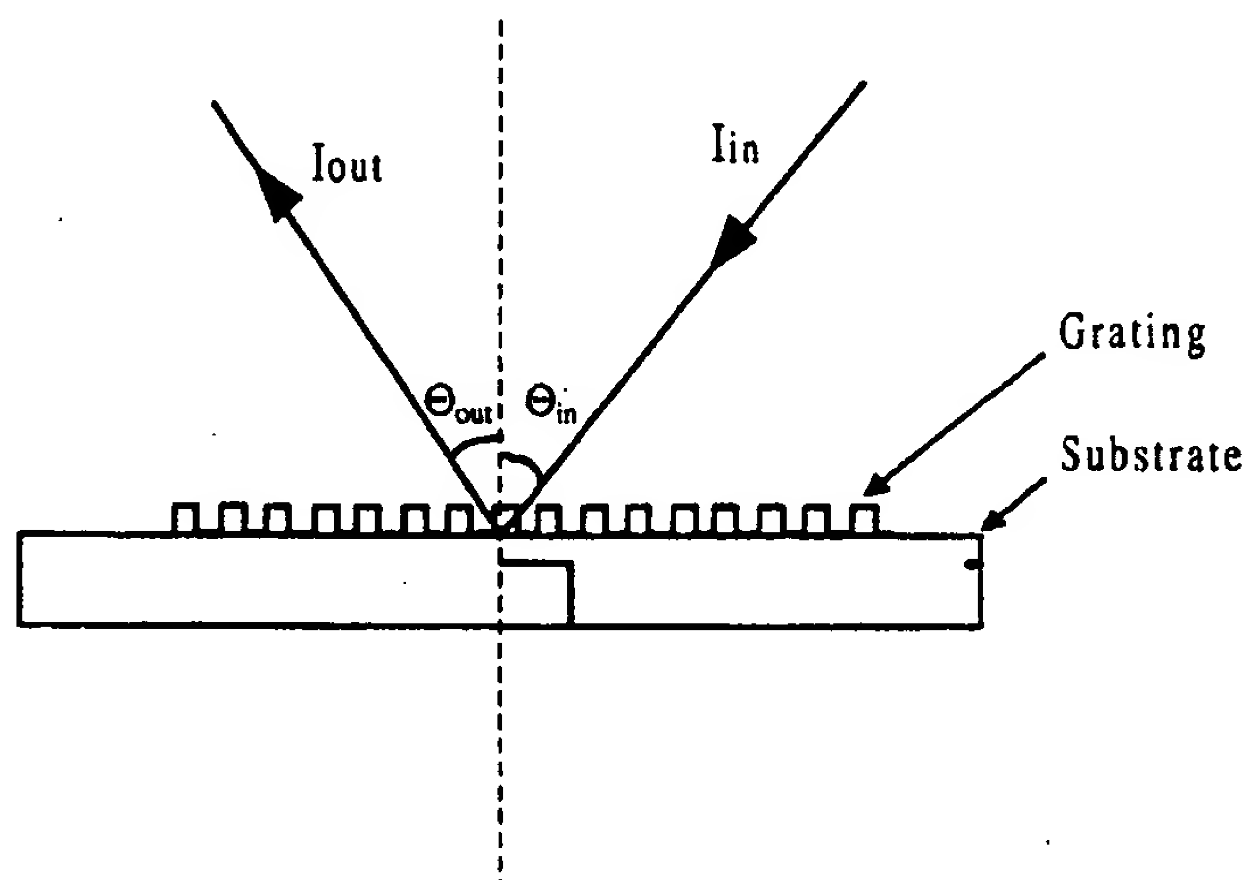

Figure 1. Illustration of scatterometry fundamentals.

The dependency of the reflectance on these various parameters can be utilized to characterize the target structure. A periodic target is constructed to simulate the circuit pattern size and density to be controlled. The reflectance is measured as a function of the angel of incidence, Θ_{in}, or as a function of the wavelength, λ, as shown in Figure 2.

The physical reason for the variation of the reflectance is that the incident light interacts with the grating as well as with possible multilayers between the grating and the substrate. These interactions, which are sensitive to angle of incidence and wavelength, cause different amounts of energy to be either reflected, absorbed by the substrate, and, when possible, emitted in other diffracted orders.

The effects of varying the linewidth around a nominal value are shown in Figure 3. The added lines depict the reflectivity due to ±4 nm variations from the nominal 0.18μm linewidth. Observe that the graph or reflectance signature changes due to the linewidth variation. In this way, using the different signatures for different linewidths, the linewidth for a specific sample target can be identified.

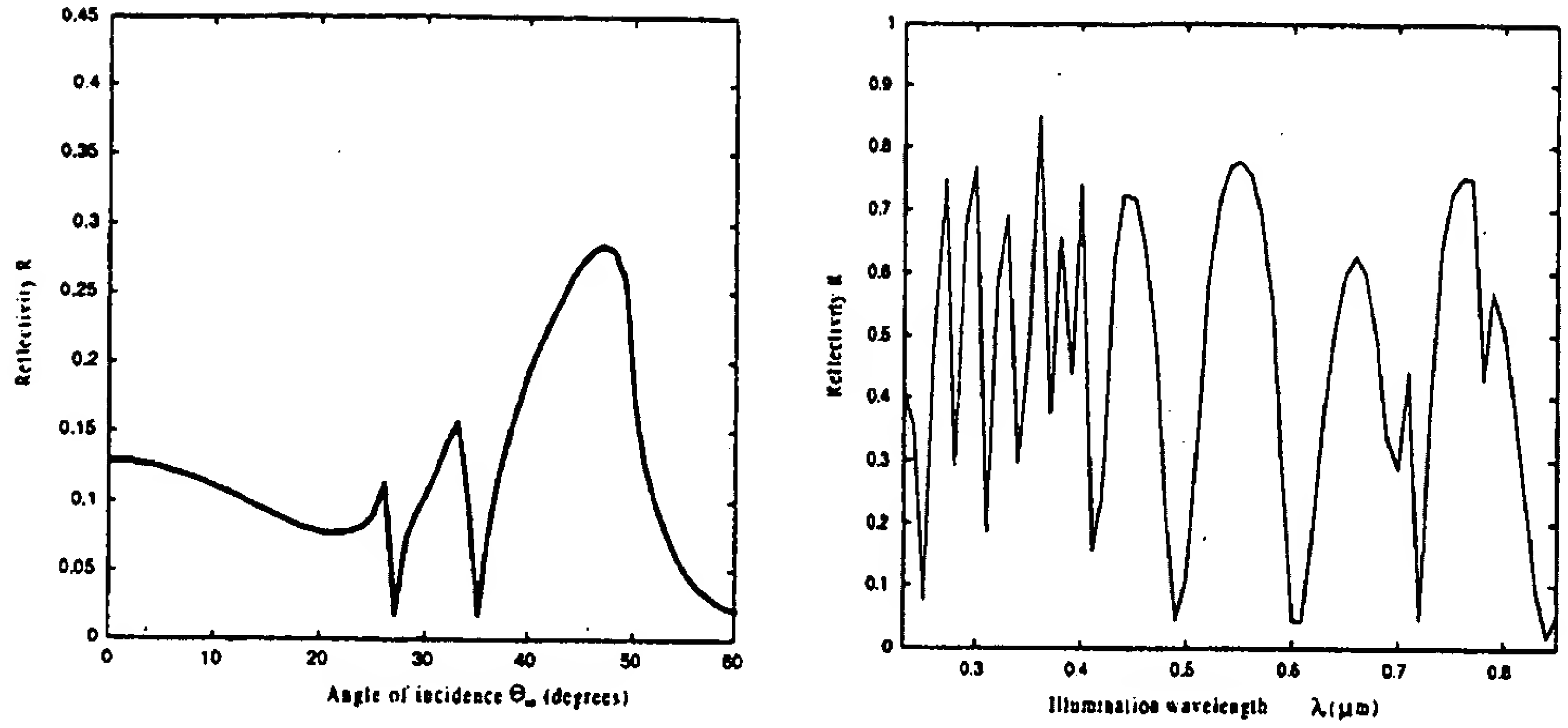

Figure 2. Reflectance, R, vs. angle of incidence, Θ_{in}, and illumination wavelength, λ (μm), from simulation of 0.18μm resist lines in a 50% duty cycle grating (1μm resist thickness, square profile, bare silicon substrate).

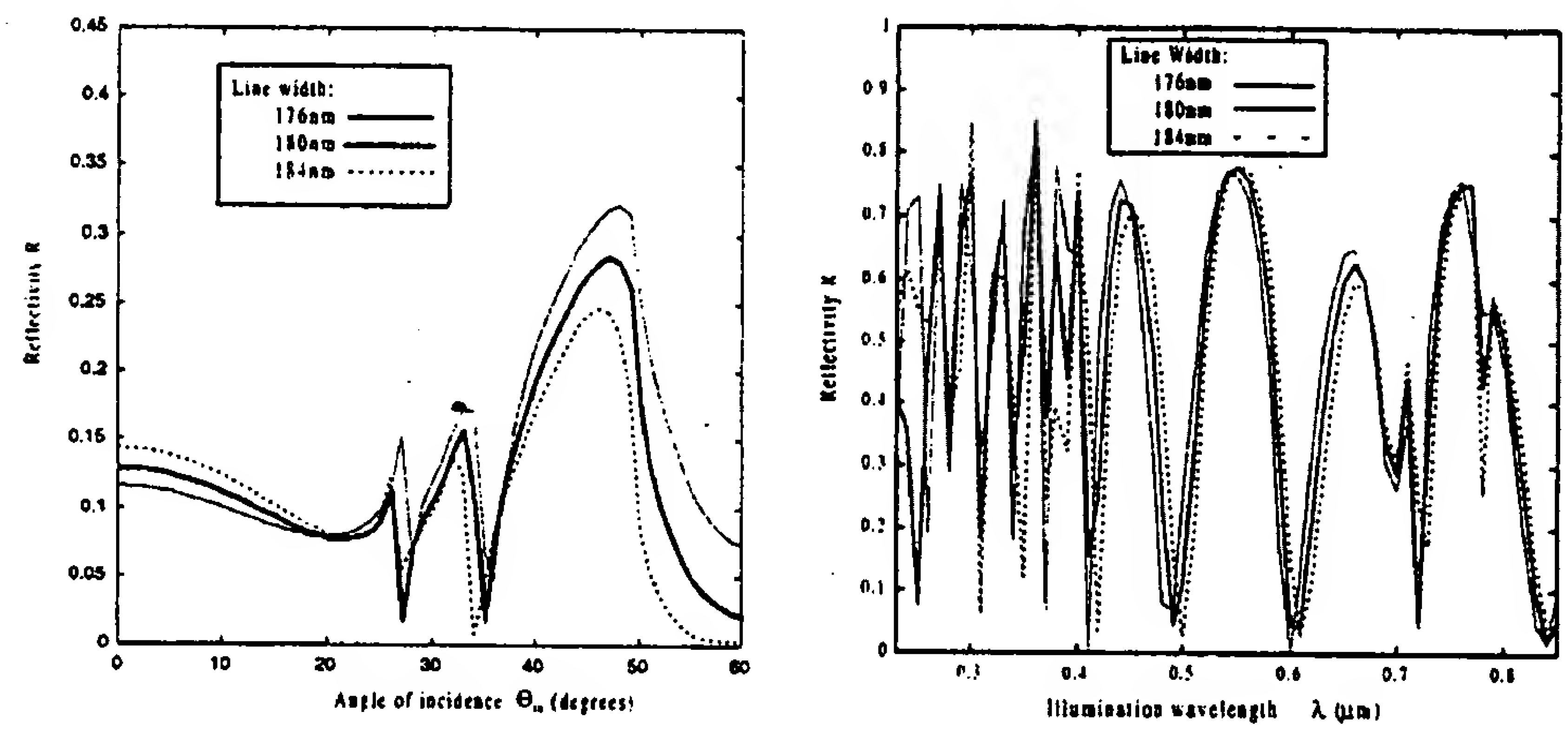

Figure 3. Reflectance, R, vs. angle of incidence, Θ_{in}, and illumination wavelength, λ (μm), from simulation as in Figure 2 with lines for 0.18μm ± 4nm added.

As previously mentioned, the reflectance, R, depends on a large number of parameters of the target structure, not only the linewidth. Variations of these parameters will thus produce their own imprints on the reflectance signatures, and the method must be able to differentiate between the effects of these parameter variations and linewidth variations.

The relationship between the reflectance curve and the grating parameters is highly non-linear and can not be solved analytically. It is almost impossible to solve the inverse-scattering problem, to find the grating parameters directly from the curve, in a practical case with the required accuracy. The approach that has been used in the practical applications involves forward modeling and pattern matching.

In order to use scatterometry for CD monitoring and control, the library signature that most closely matches the reflectance curve produced by a given sample needs to be identified. Figure 4 illustrates the basic tasks to arrive at a measurement result.

Library generation is one of the most critical aspects to achieving successful measurement results. Two types of libraries can potentially be employed, empirical and theoretical. Initially, empirical libraries may seem like a logical approach. The library is generated from a set of wafers with process parameters varied to cover the process space to be controlled. The generation and characterization of these wafers, however, is non-trivial.

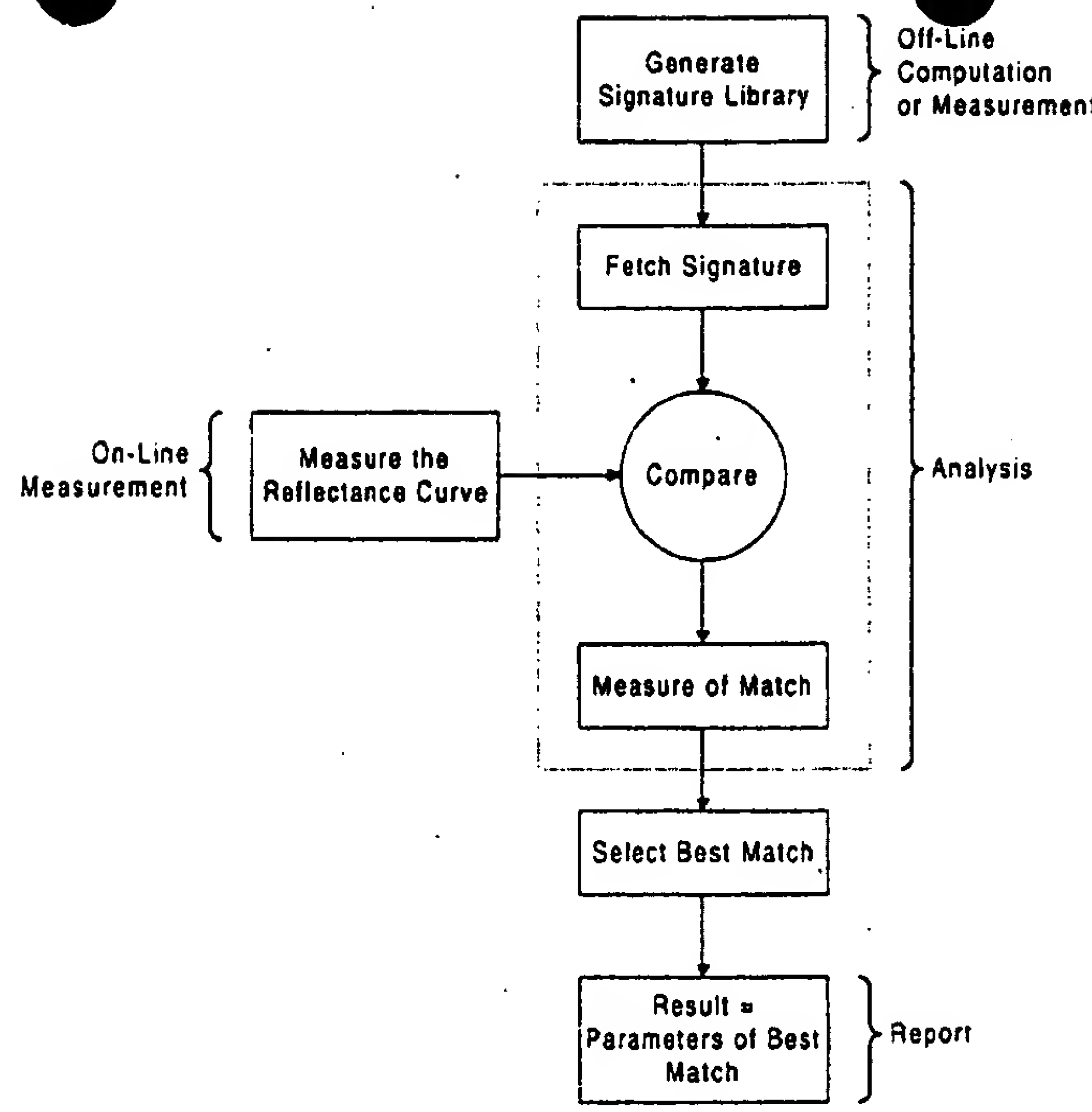

Figure 4. Application of Scatterometry.

While requiring significant computational time, theoretical libraries are easier to employ. The theoretical libraries require knowledge of the film stack properties. Film thickness, n and k values are necessary. Profiles are also needed. This information is used to generate the libraries.

A statistical difference algorithm such as Partial-Least-Squares (PLS) or Minimum-Mean-Square-Error (MMSE) is used to determine the best fit. Matches are qualified against a threshold criteria derived for the specific structures of interest. Subsequently the fit information is used to determine the parameters that correspond to the signature found in the forward problem. Matches that exceed the expected MSE threshold are flagged to the operator for further analysis. Further analysis may include visual inspection of the matched signals, library boundary checks, and reviewing the wafer on another tool such as the CD-SEM.

The signature library can be computed using rigorous diffraction modeling algorithms. Two of the better known methods are the Rigorous Coupled Wave Analysis (RCWA) [6-8] and the Classical Modal Method (CMM) [9-11]. The results presented here were obtained using the Classical Modal Method due to its superior convergence. Convergence speed is an important practical consideration when choosing a modeling method.

An example of a signature library is shown in Figure 5. Figure 5 shows the reflectance, R, as a function of the illuminating wavelength, λ, with the linewidths varying from 162nm to 198nm in 1nm increments.

Two essential requirements for the method of comparing a measured reflectance curve to a signature library are sensitivity and uniqueness. If the method must have a resolution of 1 nm, then, within the constraints of the signal-to-noise ratio, the method must be able to differentiate between the fits to two signature curves 1 nm apart in the linewidth space. Also there must be the assurance that within the relevant parameter space there is one unequivocal "best fit", so that two totally different results are not obtained from the same measurement.

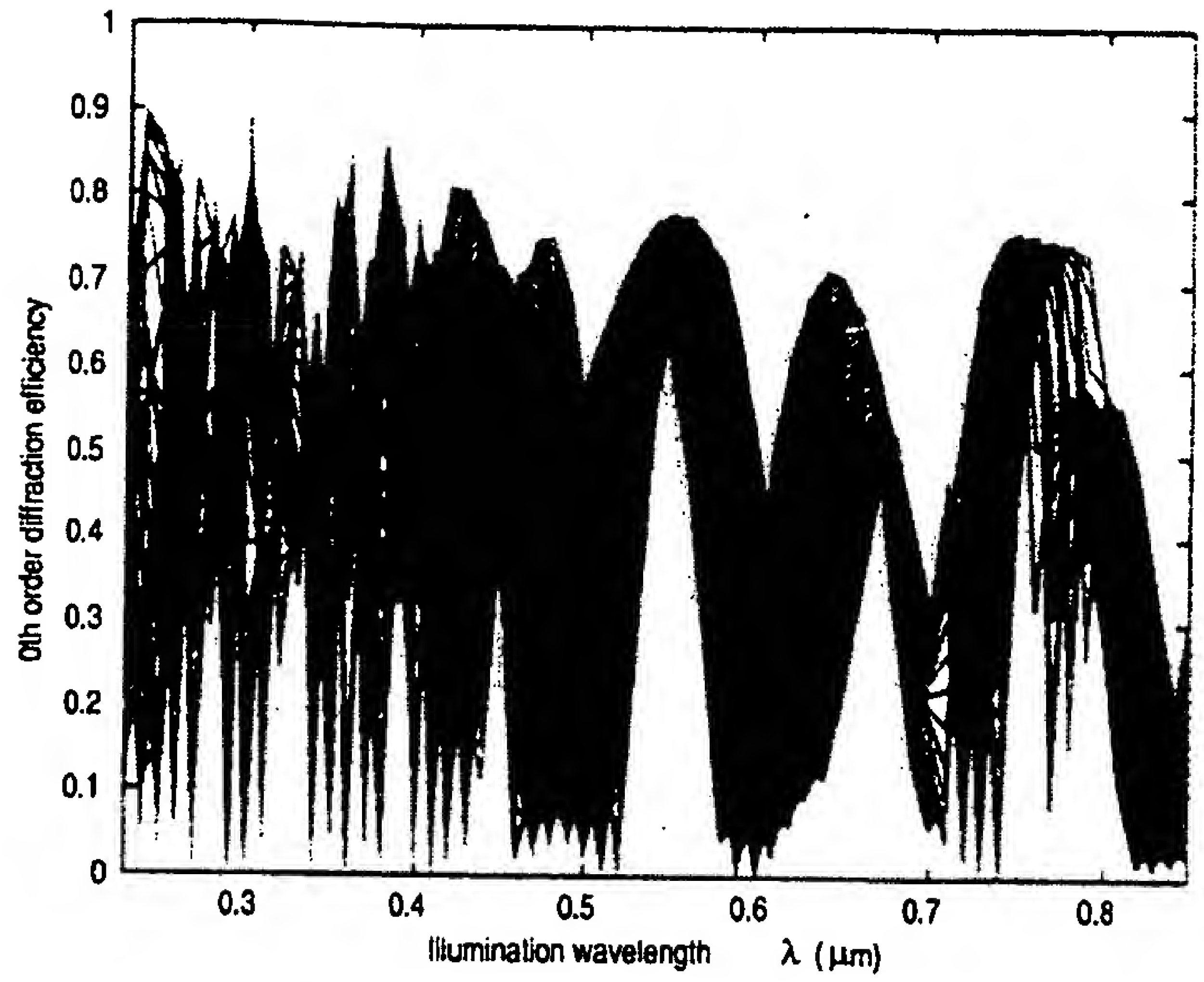

Figure 5. Reflectance, R ,as a function of the illuminating wavelength, λ.

A metric for the fit between a measured reflectance curve R_{meas} and a given curve from the signature library R_{calc} can be given by the Mean Square Error (MSE), defined by

$$MSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(R_{meas}(\lambda_i) - R_{calc}(\lambda_i)\right)^2}$$

where $R_{meas}(\lambda_i)$ is the measured reflectance at wavelength λ_i, $R_{calc}(\lambda_i)$ is the calculated reflectance (signature) at the same wavelength, and N is the number of wavelengths used.

An example of the MSE-values for angle dependent (ADS) and wavelength dependent (WDS) scatterometry is shown in Figure 6. To generate this figure, the MSE between the simulated reflectance curve for 180nm and all other curves from 162 nm to 198 nm has been calculated. As expected, the MSE between the 180nm curve and itself is zero. Note that the WDS approach has a greater change in MSE value with a one nanometer CD change than the ADS approach. This can be interpreted as the WDS approach having a greater sensitivity to one nanometer CD changes than the ADS approach.

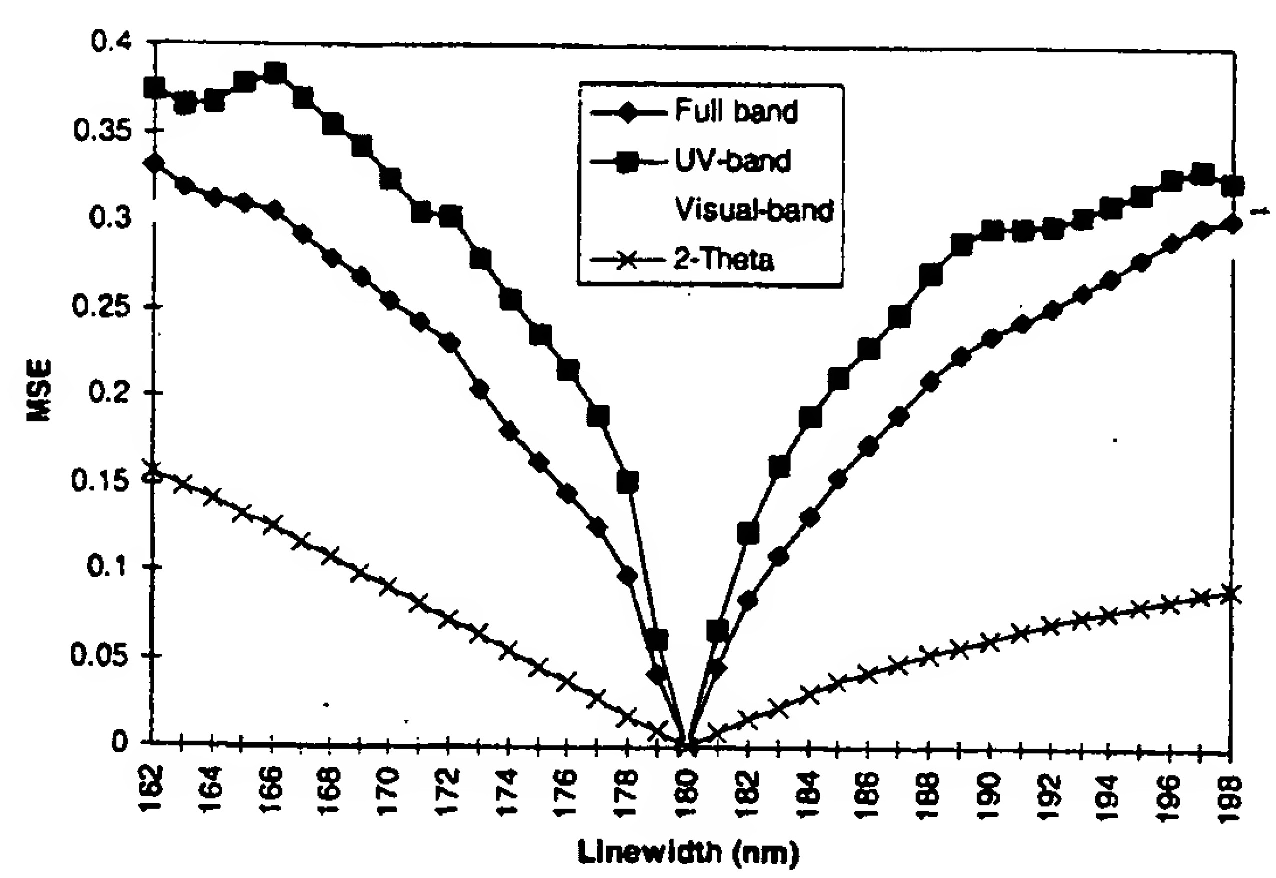

Figure 6. Example of Mean Square Error (MSE) values

Table 1 shows the MSE corresponding to 1nm CD sensitivity for nominal CD values of 100nm, 180nm, 250nm, and 350nm. The calculations have been performed for the full wavelength band (230nm...850nm), UV band (230nm...450nm), and visual band (500nm...750nm). In addition. the results have been simulated for angle dependent scatterometry (ADS).

Table 1: MSE for 1nm CD sensitivity

CD (nm)	Full band	UV band	Visual band	ADS
100	0.0780	0.1250	0.0240	0.0100
180	0.0413	0.0614	0.0226	0.0089
250	0.0339	0.0528	0.0142	0.0051
350	0.0166	0.0241	0.0097	0.0048

The highest MSE, or the most robust measurement, is in all cases obtained using the UV band. The MSE-values in this band are 5...12 times those given by the ADS, demonstrating the increased sensitivity of wavelength dependent over angle dependent scatterometry.

3. Manufacturing Process Considerations

In order to be deployed successfully in manufacturing, the scatterometry targets must fit within the available scribe area, and their behavior during changing process conditions must correlate to product. Current scribe marks typically allow room for 100x100 µm boxes. As the wafer dicing process improves, the scribe mark area will decrease to allow more die per wafer.

The minimum scatterometry target size is controlled by the effective spot size of the incident probe. The intensity distribution of the light spot includes a main peak at the center and a fringe pattern around it as illustrated in Figure 7. Most of the illumination intensity is in the central part of the spot. The fringes are caused by light diffraction at apertures and optical elements in the incident beam path.

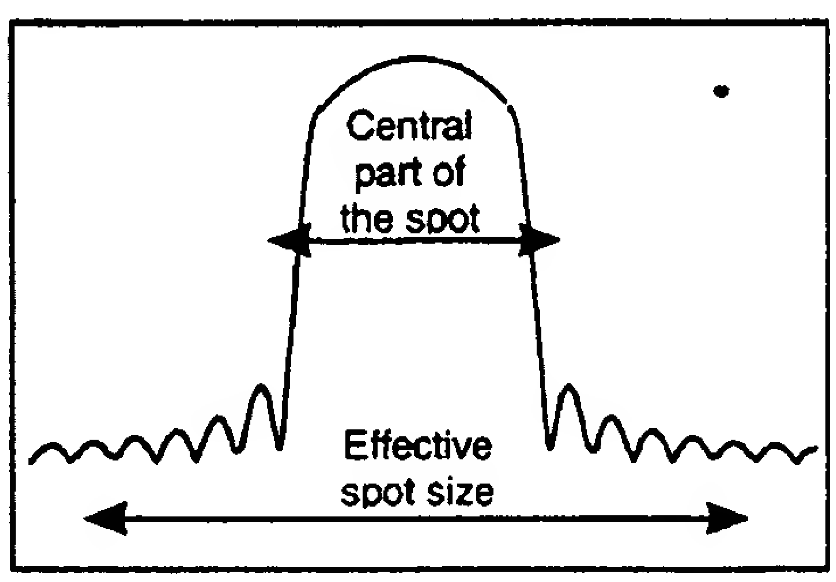

Figure 7. Diffraction and interference affect the spatial distribution of the light intensity in the vicinity of the illumination spot

As the spot is stepped to the edge of the target, the contribution of the fringes to the reflectivity signal will diminish. The point at which this causes an increase in the mean square error value defines the minimum target size. Characterization of the prototype and beta platforms determined a required target size of 100 µm and 50 µm, respectively.

For present CD SEM metrology, CD structures are employed to track process shifts. Good correlation of these structures to circuit features has been observed under changing process conditions. When monitoring line and space behavior, dense, one-to-minimum pitch and isolated features are measured. For scatterometry, dense lines provide adequate signal strength to obtain reliable measurements. The question

arises as to what is an adequate separation distance to simulate an isolated line. Typically, 1:5 line pitch is considered to be isolated and correlates well to truly isolated features, greater than 1:5 line pitch.

4. Comparison to Existing Metrology Methods

Several studies have been conducted to compare scatterometry to other metrology techniques including CD SEM, AFM, and x-section SEM. Niu, *et al* observed excellent correlation for wavelength dependent scatterometry to AFM for resist on an anti-reflective coating on a silicon substrate [5]. Profile mismatches may have been caused by AFM tip effects. Bushman, *et al* compared angle dependent scatterometry to AFM, in-line CD SEM and x-section SEM for an etched focus exposure matrix on a typical gate stack [3]. Scatterometry and AFM were shown to be the only two in-line techniques suitable for determining CD profiles. Also, scatterometry was shown to be sensitive to properties of the film structure including thickness and extinction coefficient, k. Baum, *et al* compared scatterometry results to an in-line CD SEM [4]. Linear correlation was observed for linewidths ranging from 50 to 290 nm for an etched gate stack. A gauge study was conducted for the four layer stack prior to etch, and a precision of 1.53 nm, 3σ was obtained.

The authors have performed similar studies. It has been observed that scatterometry is sensitive to CD, profile, film thickness, n and k for the patterned structure and the underlying film stack. Several film stacks were prepared to study these sensitivities.

In this study, resist on silicon, focus exposure wafers were prepared using approximately 0.6 µm of resist on bare silicon. 0.25 µm features were patterned at 1:1 and 1:5 pitch. An anti-reflective coating was not employed so that features with standing waves could be generated. The sensitivity of the technique to standing waves is one of many questions posed by the authors. Scatterometry, CD-SEM, AFM and x-section SEM measurements were obtained. The results are summarized in Table 2.

Table 2. Summary of Measurement Results.

CD 250 L/S 1:1	CD-SEM	AFM	Cross Section SEM	Scatterometry
CD Top	0.230	0.185	0.192	---
CD Middle	0.256	0.228	0.217	0.205
CD Bottom	0.285	0.269	0.215	---
Step Height	---	0.550	0.512	0.568
SWA Left	---	85.3		
SWA Right	---	84.6		

CD 250 L/S 1:5	CD-SEM	AFM	Cross Section SEM	Scatterometry
CD Top	0.159	0.128	0.139	---
CD Middle	0.192	0.174	0.167	0.182
CD Bottom	0.223	0.195	0.173	---
Step Height	---	0.455	0.493	0.501
SWA Left	---	84.1		
SWA Right	---	84.0		

As noted in Table 2, there are offsets between the various measurement techniques. Currently, cross section SEM is normally employed to characterize transistors during development. The AFM and scatterometry CD results are closest to the cross section results highlighting their potential use for in-line characterization. The CD SEM results have the furthest offset from the cross section results and contain no height information. Finally, the delta between the scatterometry and cross section SEM height results could be due to a number of factors. First, note that the cross section measurements are a single point

measurement and the Scatterometry measurements are an average over a number of line space pairs. Secondly, the manual selection of points for height determination on the cross section image is subjective. Lastly, the rectangular model used for library generation may not accurately represent the standing wave effects exhibited in the lines. Further characterization is being done in these areas. Additionally, none of the tools were specifically calibrated for this test. It is expected that optimization could bring CD-SEM results in closer. Figure 8 shows a graphical depiction of the measurement results.

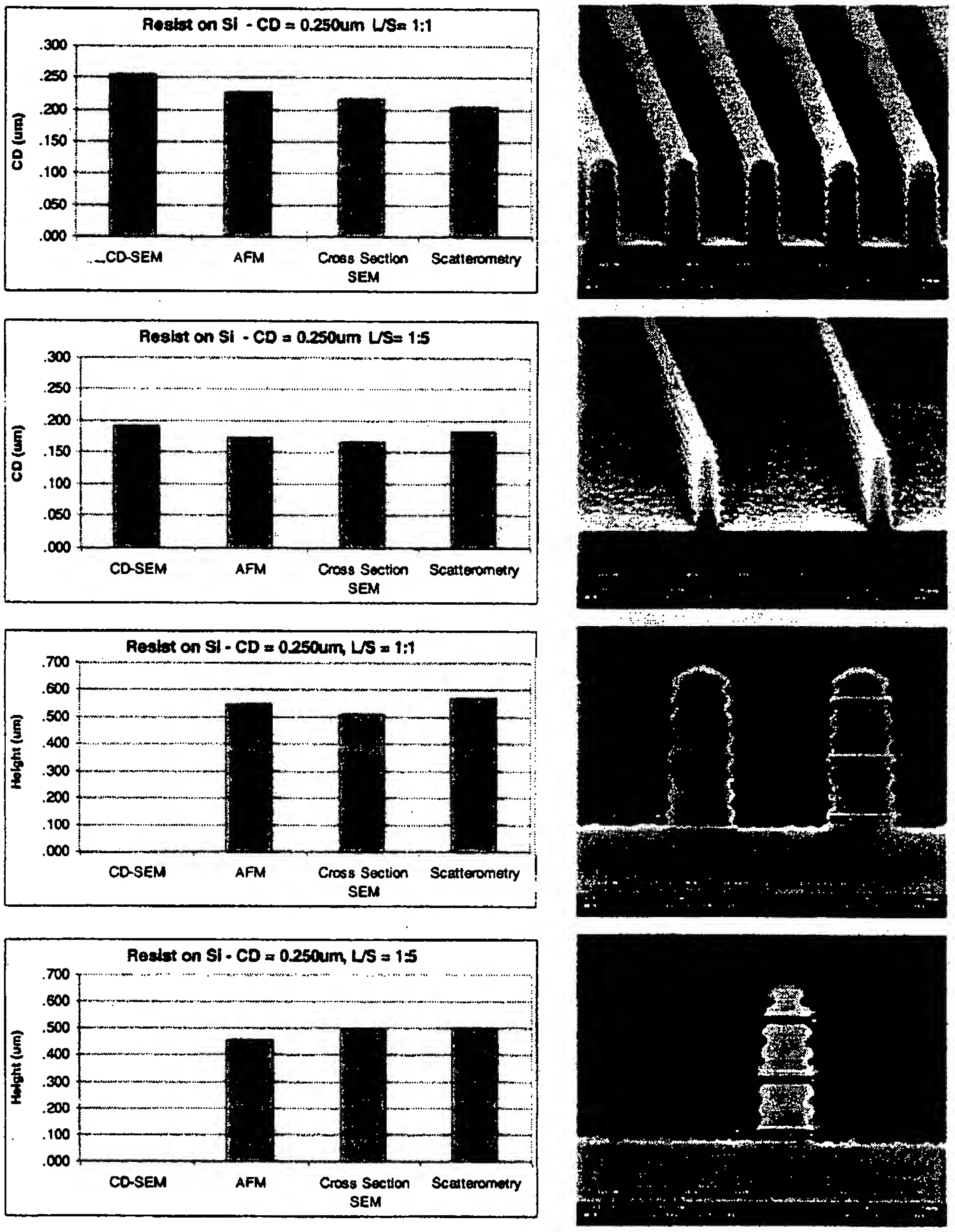

Figure 8. CD and height measurement results for resist on silicon, 0.250 µm, L/S 1:1 and 1:5.

5. Repeatability and Matching

CD and height repeatability measurements were performed on nine sites. The CD repeatability ranged from 0-3.6 nm, 3σ, for the dense features and from 0-1.5 nm, 3σ for the isolated features. The height repeatability ranged from 0-7 nm, 3σ for the dense features and from 0-6 nm, 3σ for the isolated features. In previous studies of etched silicon features, CD and height repeatability numbers of 1 nm and 1.9 nm, 3σ, respectively, have been obtained. The larger numbers observed here are most likely due to the two dimensional library which does not account for sidewall slope or standing waves. Further libraries are being constructed to study these effects.

Figure 9 shows the measurement traces for an etched silicon sample on three different tools for studying system to system matching. The CD and Height values for these traces were exactly the same. The small differences in the measurement traces did not effect the results obtained from this library. Future work will involve additional libraries, targets, and systems.

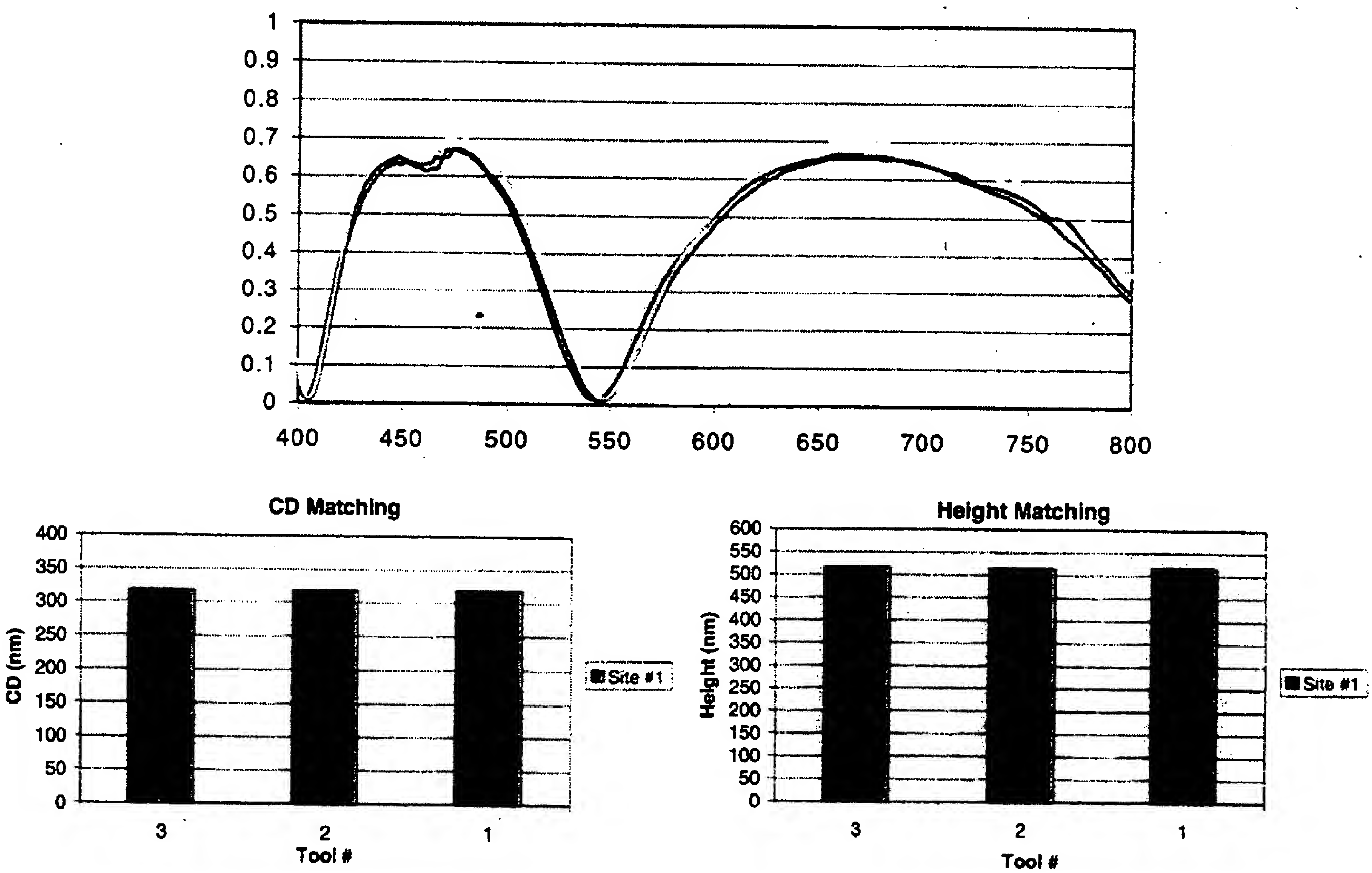

Figure 9. Measurement traces from three systems for an etched silicon sample and the corresponding CD and Height results.

6. Conclusion

Spectroscopic Scatterometry appears to be capable of meeting the requirements of the International Technology Roadmap for Semiconductors. The measurement targets can be integrated into current process control strategies. Scatterometry is capable of fully characterizing a target structure by providing CD, sidewall angle, thickness, and optical properties of the film stack. Wavelength dependent scatterometry is more sensitive to one nanometer CD changes than angle dependent scatterometry. MMSE has been found

to be a reliable, accurate, and rapid criteria for library matching. Tool performance, in terms of accuracy and repeatability, is dependent upon the quality of the modeled library. System to system matching has been demonstrated to within one nanometer. Finally, the technology is suitable for integration into the photolithography cell.

7. References

1. J. McNeil, S. Naqvi, S. Gaspar, K. Hickman, K. Bishop, L. Milner, R. Krukar and G. Petersen, "Scatterometry Applied to Microelectronics Processing," *Microlithography World*, pp. 16-22, Nov./Dec. 1992.
2. M. Murnane, C. Raymond, S. Prins, S. Naqvi and J. McNeil, "Scatterometry for 0.24 μm – 0.70 μm Developed Photoresist Metrology," *Proceedings of the SPIE*, Vol. 2439, pp. 427-436, Mar. 1995.
3. S. Bushman and S. Farrer, "Scatterometry Measurements for Process Monitoring of Polysilicon Gate Etch," *Proceedings of the SPIE*, Vol. 3213, pp. 79-90, Oct. 1997.
4. C. Baum, R. Soper, S. Farrer and J. Shohet, "Scatterometry for Post-etch Polysilicon Gate Metrology," *Proceedings of the SPIE*, Vol. 3677, pp. 148-158, Mar. 1999.
5. X. Niu and S. Yedur, "Specular Spectroscopic Scatterometry in DUV Lithography," *Proceedings of the SPIE*, Vol. 3677, pp. 159-168, Mar. 1999.
6. M. Moharam and T. Gaylord, "Rigorous Coupled-wave Analysis of Planar-grating Diffraction," *J. Opt. Soc. Am.*, Vol. 71, No. 7, Jul. 1981.
7. M. Moharam and T. Gaylord, "Diffraction Analysis of Dielectric Surface-relief Gratings," *J. Opt. Soc. Am.*, Vol 72, No. 10, Oct. 1982.
8. T. Gaylord and M. Moharam, "Analysis and Applications of Optical Diffraction by Gratings," *Proceedings of the IEEE*, Vol. 73, No. 5, May 1985.
9. Lifeng, Li, "A modal analysis of lammellar diffraction gratings in conical mountings," *J. Modern Optics 40*, 553-573 (1993).
10. Lifeng, Li, "Multilayer modal method for diffraction gratings of arbitary profile, depth, and permittivity," *J. Opt. Soc. Am.*, A10, 2583-2501 (1993), Addendum. *J Opt. Am A11*, 1685 (1994).
11. Lifeng, Li and Charles, Haggans, "Convergence of the coupled-wave method for metallic lamellar diffraction gratings," *J. Opt. Soc. Am.*, A 10, 1184-1189 (1993).

Specular Spectral Profilometry on Metal Layers

Junwei Bao, Xinhui Niu, Nickhil Jakatdar, Costas Spanos, Joseph J. Bendik
(JB, NJ, CS, UC Berkeley, CA 94720)
(XN, Timbre Technology, Inc, Fremont, CA 94538)
(JJB, Rancho Bernardo, CA 92127)

With the advent of deep sub-micron semiconductor technology, metrology for metal interconnects becomes more critical. In addition to the line width, information about the height and the sidewall profile is needed to ensure good circuit performance. Conventional metrology tools such as CD SEMs and AFMs are either unable to measure the profile, or too slow for production process control.

Scatterometry is a promising candidate as an *in situ*, full-profile metrology tool [1]. In this method, scattering of broadband light (240 nm to 760 nm) on periodical structures is simulated by approximating the structure with a finite series of Fourier expansion terms [2]. By comparing the measured spectrum and the simulated spectra for various possible profiles in a pre-calculated library, the profile can be extracted. Previous work has shown good results on resist structures. For metal structures, however, more diffraction orders need to be included to accurately simulate light scattering. In this study, a library for 0.22 μm line and 0.44 μm space metal grating structures is generated using 31 orders. The profiles of metal grating structures of the same size are extracted using this library. Our data shows that the correlation between CD-SEM and scatterometry-based profile extraction appears to be related to the sidewall angle of the profile. These discrepancies will be analyzed and discussed.

Keywords: Specular spectroscopic profilometry, DUV lithography, spectroscopic ellipsometry, metal layer metrology.

1. INTRODUCTION

As the semiconductor industry moves beyond 0.18 μm, process variation has an increasing impact on the features printed on the wafer, and metrology becomes more critical for process control. With continuing technology scaling into the deep sub-micron regime, interconnect constitutes an increasing portion of the overall circuit delay [3]. Not only line width, but also height and sidewall profile measurements are required to accurately characterize RC delay. (Figure 1)

In *Metrology, Inspection, and Process Control for Microlithography XIV*, Neal T. Sullivan, Editor, Proceedings of SPIE Vol. 3998 (2000) • 0277-786X/00/$15.00

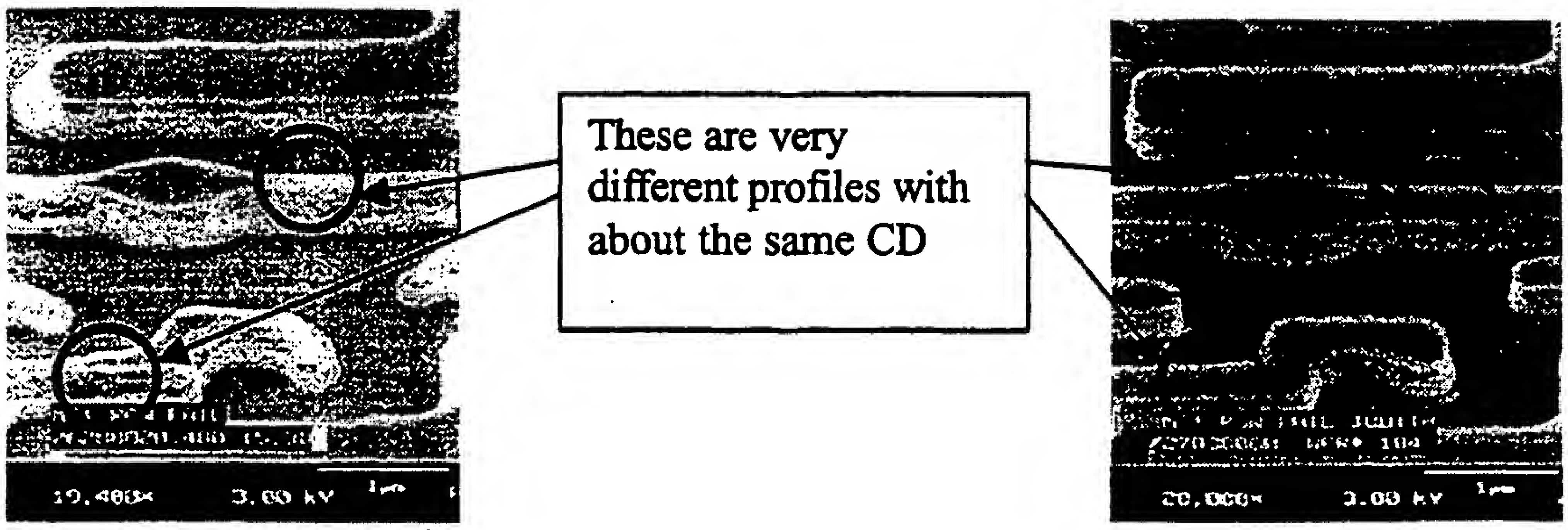

Figure 1. Metal interconnect profile variation.

Metrology is a key element in maintaining adequate process latitude for acceptable profile in lithography and etch processes. Accurate full-profile metrology is needed for characterizing and monitoring exposure, focus, post exposure bake (PEB), plasma etch, etc. [4] [5]. Various techniques have been both proposed and implemented for measuring patterned features, such as visual test-based methods, atomic force microscopy (AFM), cross-sectional and top-down CD scanning electron microscopy (SEM), etc. These techniques are either expensive, time-consuming, destructive, or not accurate enough. Further, by their nature, they cannot be deployed *in situ*.

Optical metrology is a good candidate for overcoming the disadvantages of the metrologies mentioned above. Many methods have been proposed in this area. Kleinknecht and Meier used diffraction grating test patterns for monitoring linewidths on IC structures [6]. Damar, Chan, Wu and Neureuther used an automated He-Ne laser spectrometer to explore the fundamental issues associated with nondestructive IC process monitoring by diffraction from drop-in test sites [7]. Tadros, Neureuther and Guerrieri used a massively parallel computer simulation algorithm to investigate electromagnetic scattering and optical imaging issues related to linewidth measurement of polysilicon gate structures [8]. Tadron *et al* in [8] did pioneering work in the area of using diffraction gratings as test structures, and a spectroscopic reflectometer as the data collection tool. They showed that the broadband reflectivity (diffraction characteristics) versus wavelength had high correlation to the grating features. All these methods intended to characterize the process based on the correlation between optical responses and process conditions, and they usually deliver effective line-width values. However, no accurate profile information can be obtained from these methods.

Scatterometry is another optical diffraction technique based on the characterization of the diffraction grating structure from its optical diffraction responses. McNeil, Naqvi and co-workers have developed and demonstrated a single-wavelength, variable-angle scatterometry, or "2-θ" angle-resolved scatterometry [9]. This type of scatterometry utilizes angle-resolved measurements and characterization of diffracted light from periodic structures. Niu, Jakatdar, Bao and Spanos introduced Specular Spectroscopic Scatterometry / Specular Spectroscopic Profilometry (SSS/SSP), to measure the 0th order diffraction at a fixed incident angle and multiple wavelengths [1], [10]. This was the first technique that took the phase of the optical signal into consideration, in addition to the magnitude information. Due to its fixed angle, specular spectroscopic profilometry is easy to deploy. It can directly utilize conventional spectroscopic ellipsometers or spectroscopic reflectometers, and can be easily installed *in situ* or inline.

Previous work using SSP has shown good results on resist lines on poly layer [1], [10]. In this paper, we extend this work to resist lines on metal layers and etched metal features, and discuss some possible application to damascene process metrology.

2. SPECULAR SPECTROSCOPIC PROFILOMETRY

Specular Spectroscopic Profilometry measures the 0th order diffraction responses of a grating at multiple wavelengths. Diffraction response for the rest of the document will refer to both the magnitude and phase of the diffracted signal in the case of an ellipsometer, and just magnitude in the case of a reflectometer. Given the 0th order diffraction responses, one can then attempt to reconstruct the grating profiles. Conventional spectroscopic ellipsometry and reflectometry equipment can be used.

A spectroscopic ellipsometer is used in this work for measurements of 1D gratings. The ratio of the 0th order complex transverse electric (TE) and transverse magnetic (TM) reflectivity $\rho = r_{p,0} / r_{s,0} = \tan\Psi e^{j\Delta}$ is measured, where $r_{p,0}$ is the 0th order TM reflectance coefficient and $r_{s,0}$ is the 0th order TE reflectance coefficient.

The extraction of a CD profile can be viewed as an optimization problem. The objective is to find a profile whose simulated diffraction response matches the actual measured response. For practical inline usage we propose a library-based methodology for CD profile extraction. Details of this method can be found in [11].

3. EXPERIMENTAL RESULTS AND DISCUSSION

In the first experiment, photoresist features on metal films were measured using specular spectroscopic profilometry. The stack is developed resist on anti reflective coating (ARC) on thin film layers, which consist of TiN on Al on TiN on Ti on TEOS, as shown in Figure 2. The feature we study is a one-dimensional grating, with line/space of 0.22/0.44 μm. The grating area under test is 250 μm by 250 μm.

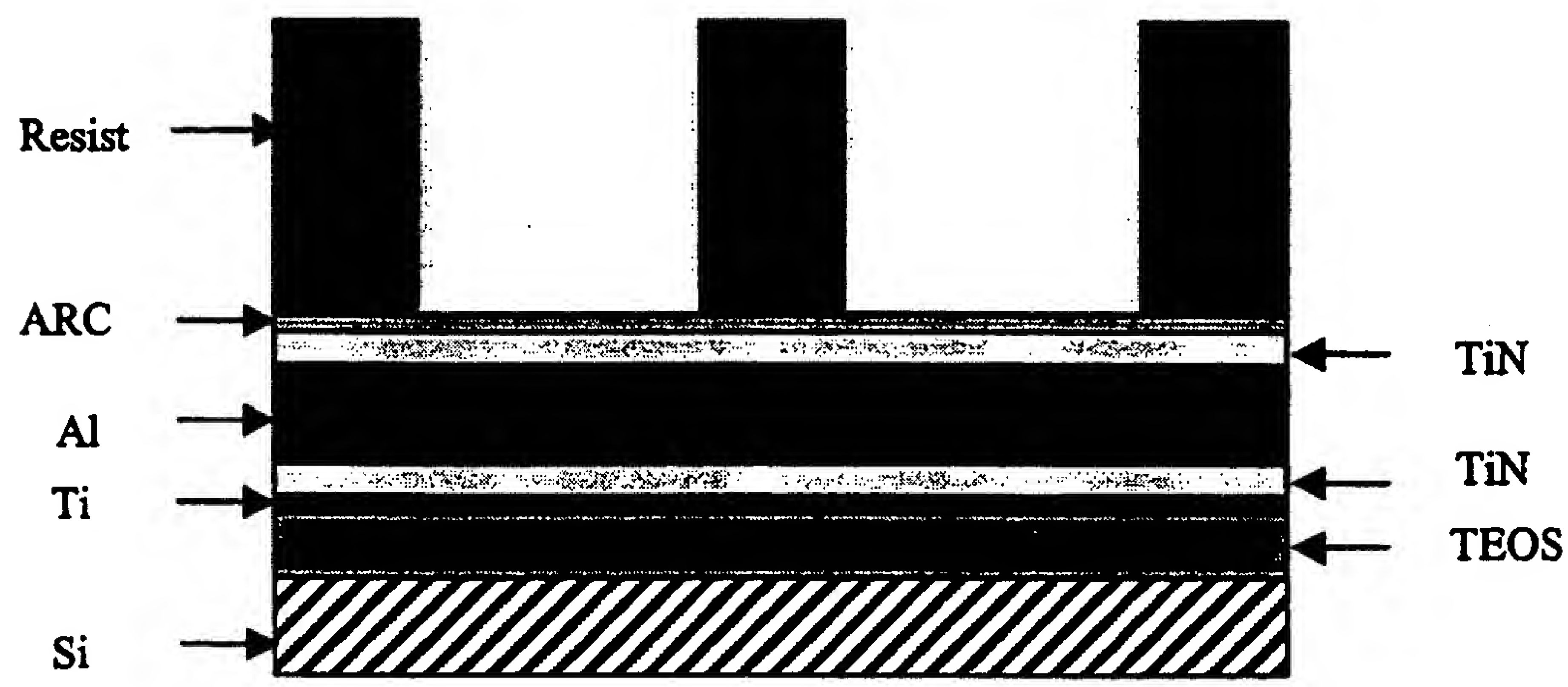

Figure 2. Stack layer for patterned resist features on metal thin films.

A focus exposure matrix (FEM) is printed on Shipley's UV6 resist using ASML DUV stepper. Focus was set from –0.4 μm to 0.2 μm with a step of 0.15 μm, and exposure doses were set from 21.9 mJ/cm^2 to 29.1 mJ/cm^2 with a step of 1.2 mJ/cm^2. After exposure and PEB, the resist is developed. A KLA-Tencor 1280 spectroscopic ellipsometer is used to measure the response (the ratio of the 0^{th} order TM and TE reflectance) at an incidence angle of 70°. Twenty-two dice were measured, and the extracted resist profiles are shown in Figure 3 in the same layout as they are on the wafer. The profile distribution across the wafer looks quite reasonable for an FEM.

We also performed CD SEM measurements on these gratings, and compared the bottom CD measurement produced from SSP and CD SEM, as plotted in Figure 4. The two data sets show good correlation. The deviation is mostly due to the constant offset for the CD SEM, which is a well-known phenomenon. Some of the deviations between the two metrologies are not consistent with others. Upon further examination, we found that those deviations correspond to profiles that have small sidewall angles or some footing, which makes CD SEM measurements problematic.

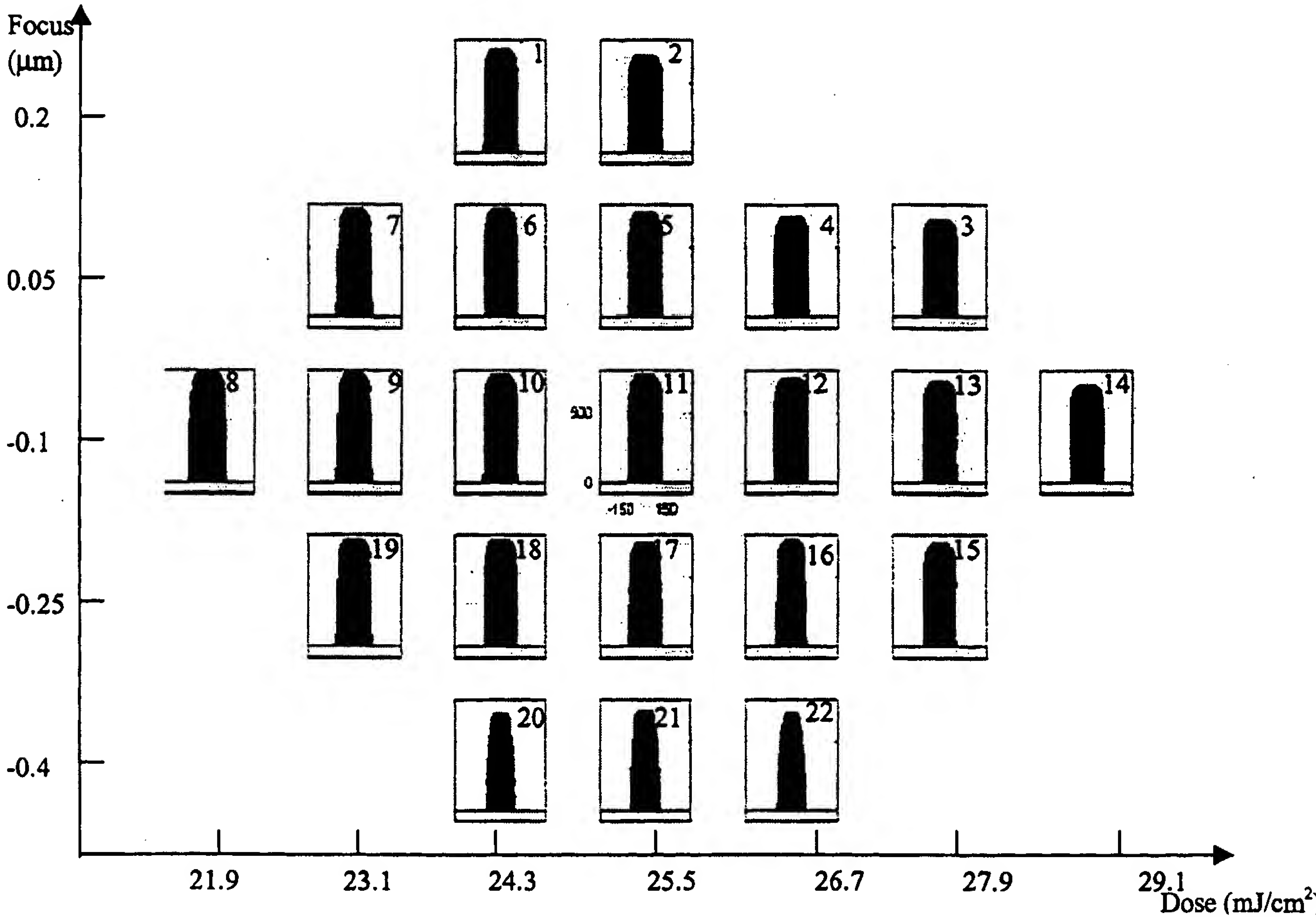

Figure 3. Extracted FEM resist profiles plotted as their positions on the wafer. All figures are in the same scale. The numbers on the upper right corners are site numbers.

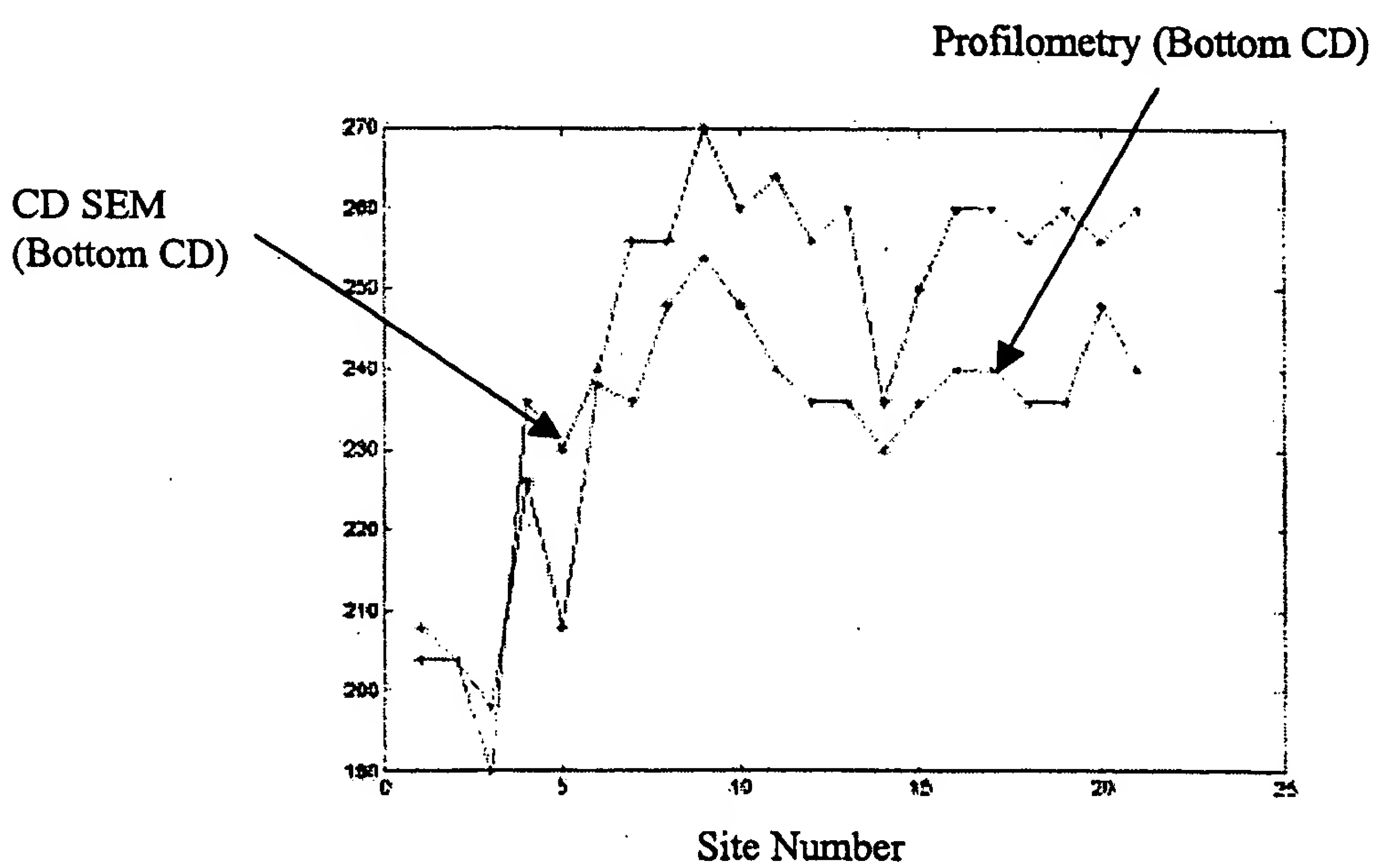

Figure 4. Comparison of profilometry and CD SEM bottom CD.

The FEM was then patterned onto the metal layer using plasma etching, and the resist and ARC were removed. The resulting stack of patterned metal features (TiN on Al on TiN on Ti) on TEOS thin film on silicon wafer is shown in Figure 5.

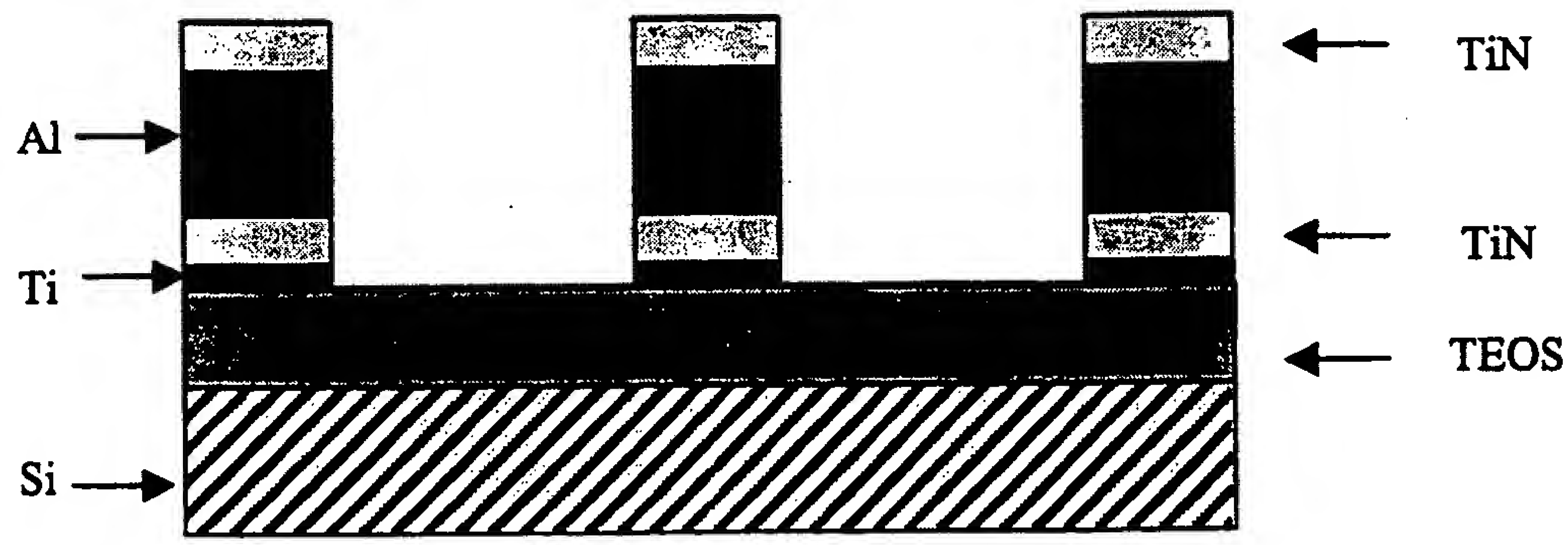

Figure 5. Stack structure for patterned metal features.

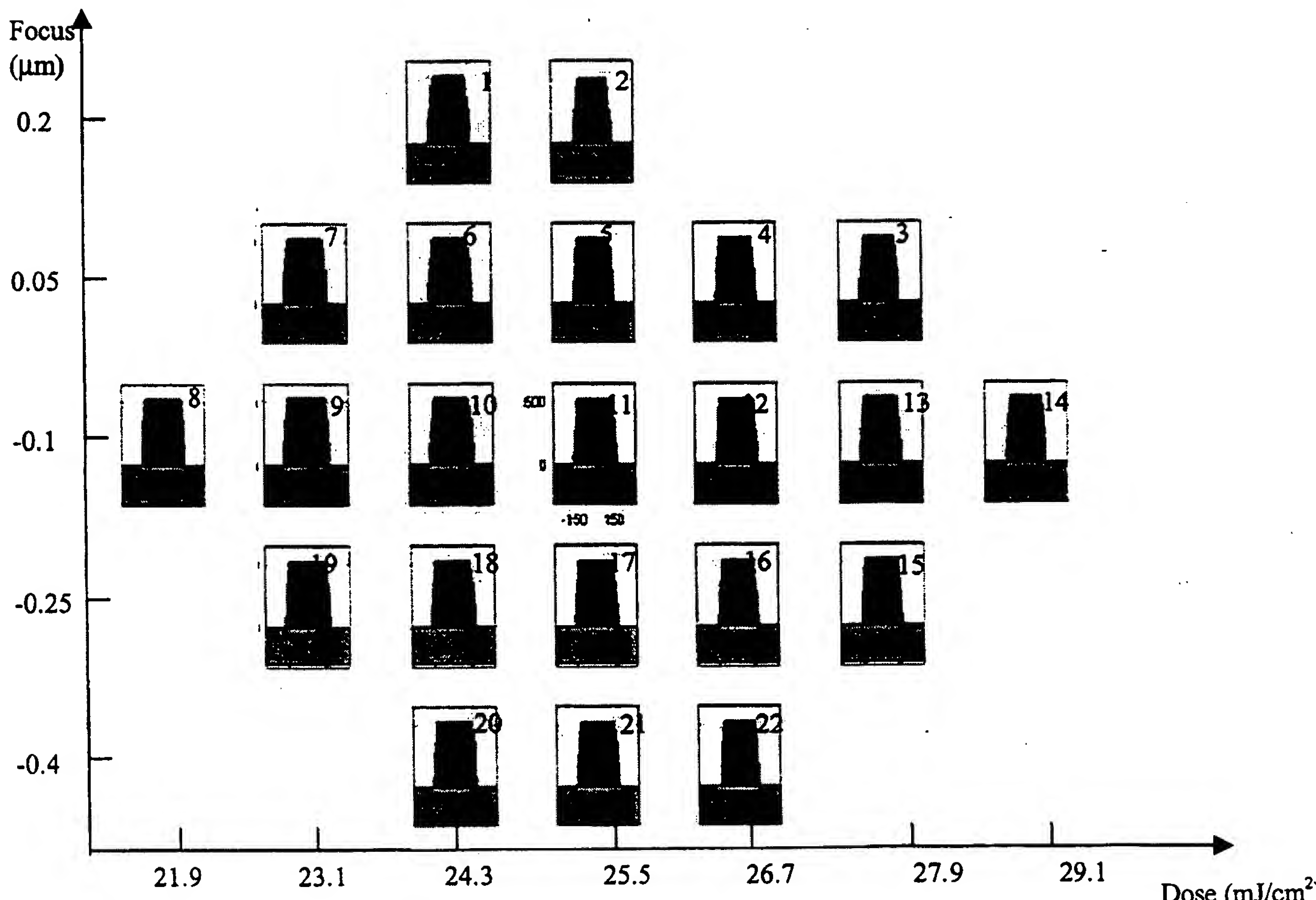

Figure 6. Extracted FEM metal profiles plotted as their positions on the wafer. All figures are in the same scale. The numbers on the upper right corners are site numbers

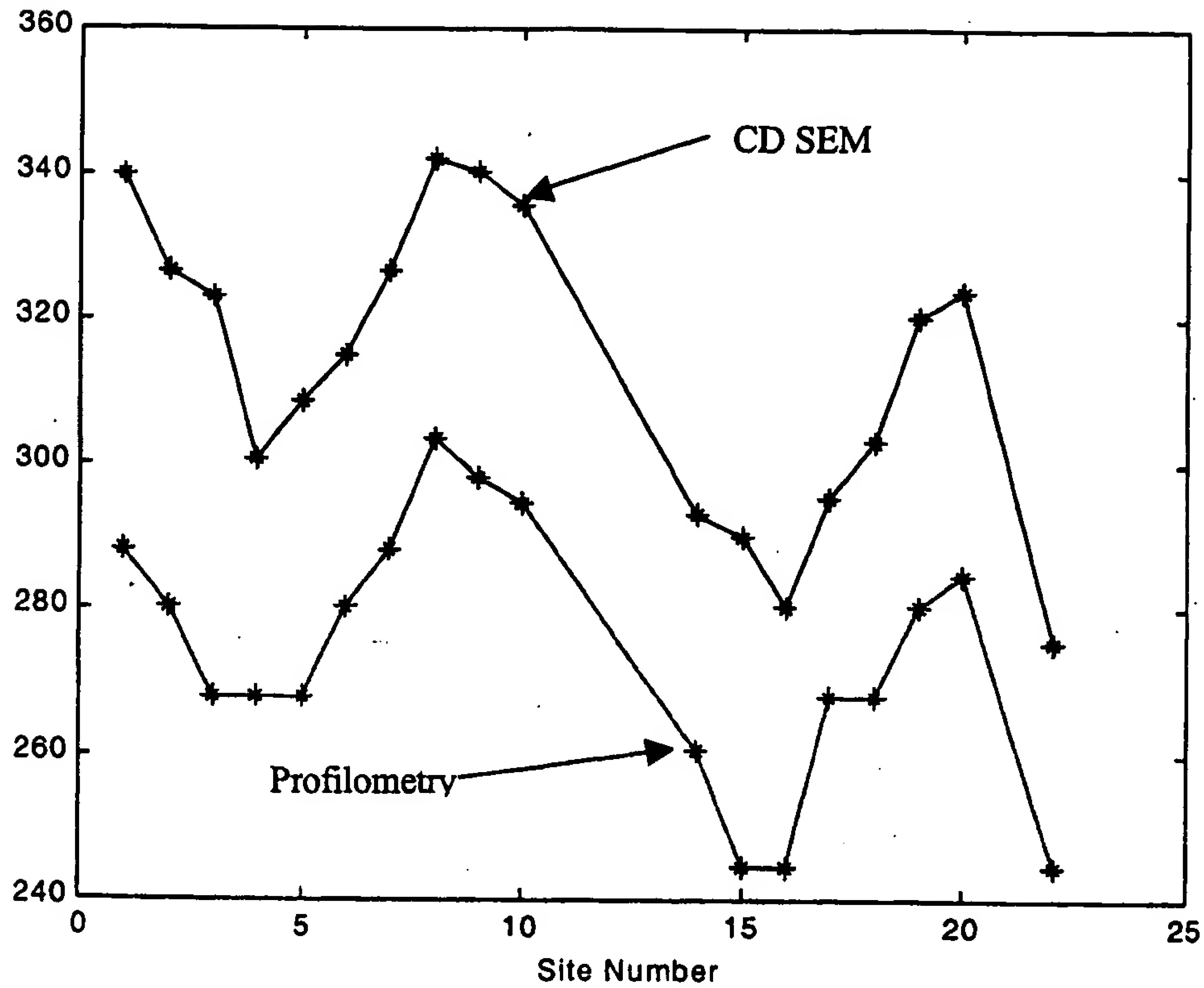

Figure 7. Comparison of profilometry and CD SEM top CD for metal features. CD SEM has no valid measurements at the missing data points

The KLA-Tencor ellipsometer was used to measure the response from the metal gratings. Again 22 dice were measured and the profiles were extracted, as shown in Figure 6. CD SEM measurements were also made, and the comparison of top CD from both methods is plotted in Figure 7. We can see that the deviation between CD SEM and profilometry is more consistent than the result for resist features in Figure 4, because the sidewalls for the metal profiles are fairly straight compared to those for the resist profiles. We also note that the SEM charging effect which can distort photoresist measurements is much less significant when measuring metal features. This helps the CD SEM get more consistent results.

To study the effect of sidewall angles on CD SEM measurements, we take our spectroscopic profilometry as the reference, and plot the deviation of CD SEM measurement versus sidewall angle, as shown in Figure 8. We can see that for smaller sidewall angles, the distribution of deviations between the two metrologies is larger. This might be because the CD SEM algorithm cannot easily determine top/bottom boundaries when the profiles are not very steep.

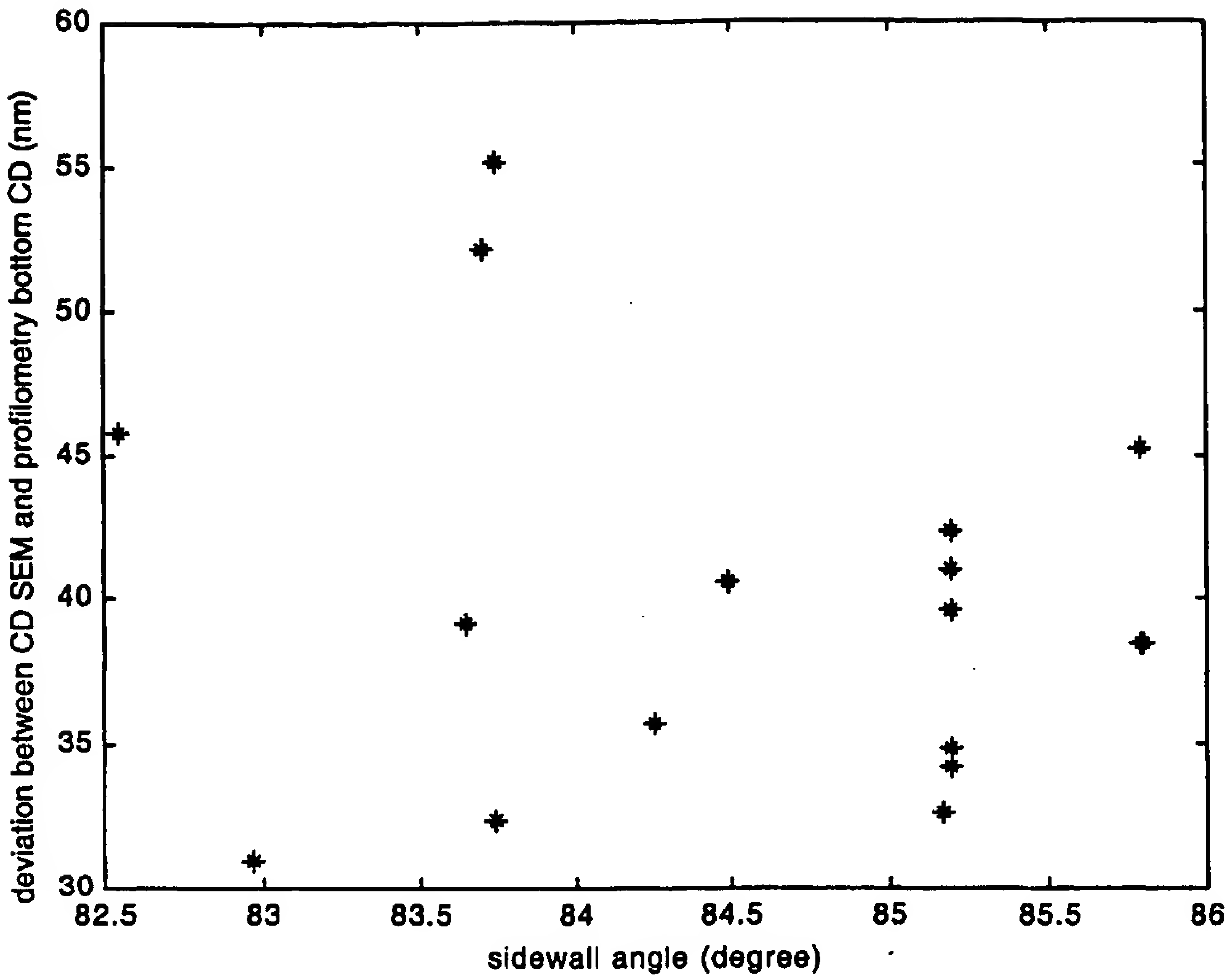

Figure 8. Deviations between CD SEM and profilometry bottom CD vs. sidewall angle.

4. PROPOSED APPLICATION FOR DAMASCENE PROCESS METROLOGY

Damascene processes bring a new, difficult challenge to CD measurement and end point detection. Several methods have been proposed based on CD SEM [12]. One is to measure CD on the dielectric lines, but this suffers from sample changing effect. Another approach is to measure the dielectric trench structure after the barrier layer is deposited. Although this would reduce the charging problem, sidewall shapes could not be characterized, and the electron beam may damage the dielectric layer.

Specular spectroscopic profilometry is a promising candidate for measuring trench profiles with or without metal filled in. It can also be used for end point detection during the CMP process, as illustrated in Figure 9. As the metal layer is being polished, the response from

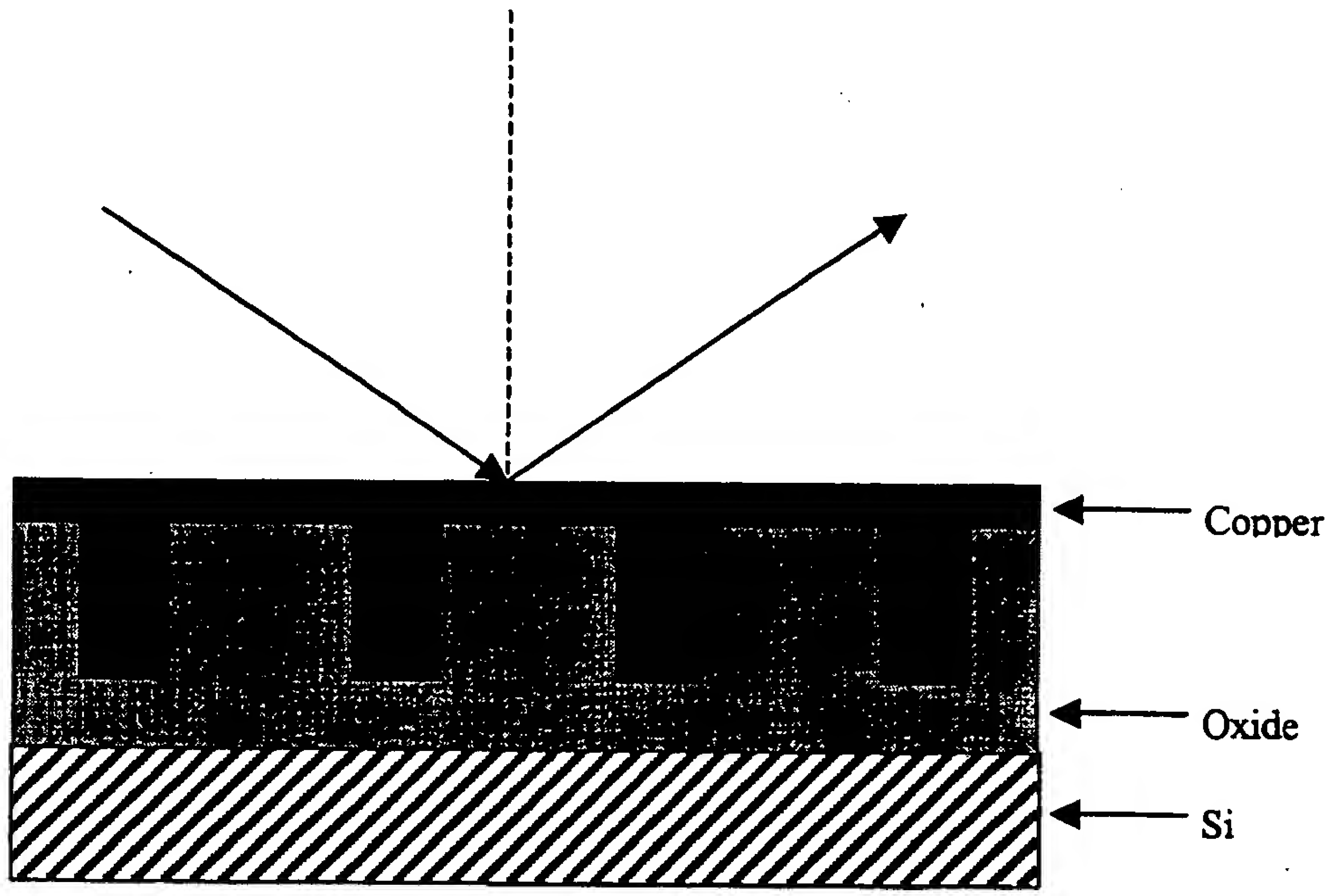

Figure 9. Typical 1D grating for monitoring damascene processes.

the structure can be measured using ellipsometry or reflectometry. At first, the signal is much like that from metal film, because most of the light going through has been absorbed. When the metal layer is getting thinner, it becomes more transparent, and the scattered light from the structure below can be detected. If the metal film thickness is included as a variable in the library [ref], the remaining film thickness can be measured and used for end point detection.

5. CONCLUSIONS

Specular spectroscopic profilometry is used to measure resist features on metal films and etched metal gratings. Full profiles of an FEM for these two structures have been extracted and good correlation with CD SEM was achieved for traditional metal structures due to better sidewall angle and less sample charging effect. We plan to test, demonstrate and use the metrology for metal line profile measurement and end point detection in the damascene process.

ACKNOWLEDGEMENTS

This work was supported by the UC-SMART program under contract #SM97-01, and by the following participating companies: Advanced Micro Devices, Atmel Corp., Applied Materials, Asyst Technologies, BOC Edwards, Cymer, Etec Systems, Intel Corp., KLA-TENCOR, Lam Research Corp., Nanometrics, Nikon Research Corp., Novellus Systems, Silicon Valley Group, and Texas Instruments.

REFERENCES

1. X. Niu, N. Jakatdar, J. Bao, C. Spanos, S. Yedur, "Specular Spectroscopic Scatterometry in DUV Lithography", *March 1999, SPIE '99, Metrology, Inspection and Process Control for Microlithography, 159 –168.*
2. M. G. Moharam and T.K. Gaylord, "Rigorous Coupled-Wave Analysis of Planar-Grating Diffraction", *J. Opt. Soc. Am., vol. 71, 811-818, July, 1981.*
3. A. K. Stamper, M. B. Fuselier, X. Tian, "Advanced Wiring RC Delay Issues for Sub-0.25-micron Generation CMOS", *Proceedings of the IEEE International Interconnect Technology Conference, 1998, 62-64.*
4. N. Jakatdar, J. Bao, C. J. Spanos, X. Niu, J. Bendik, S. Hill, "A Parameter Extraction Framework for DUV Lithography Simulation", *Proc. of SPIE, vol. 3667, 447-456, 1999.*
5. X. Niu, N. Jakatdar, C. J. Spanos, "DUV Lithography TCAD Simulator Tuning by Resist Profile Matching", *the EOS/SPIE Symposium on Microelectronic Manufacturing Technologies, May 1999.*
6. H. P. Kleinknecht, H. Meier, "Linewidth Measurement on IC Masks and Wafers by Grating Test Patterns", *Applied Optics, vol. 19, 525-533, 1980.*
7. H. S. Damar, E. P. Chan, T. T. Wu, A. R. Neureuther, "Diffraction Characterization for Process Monitoring, Linewidth Measurement and Alignment", *Proc. of SPIE, vol. 470, 157-163, 1984.*
8. K. Tadros, A. R. Neureuther, R.. Guerrieri, "Understanding Metrology of Polysilicon Gates through Reflectance Measurement and Simulation", *Proc. of SPIE, vol. 1464, 177-186, 1991.*
9. C. Raymond, M. Murnane, S. Prins, S. S. H. Naqvi, et al, "Multiparameter Grating Metrology using Optical Scatterometry", *J. Vac. Sci. Tech. B, vol. 15, no. 2, 361-368, 1997.*
10. X. Niu, N. Jakatdar, J. Bao, C. J. Spanos, "Specular Spectroscopic Scatterometry in DUV Lithography", *SRC Techon '98.*

11. X. Niu, N. Jakatdar, S. Yedur, B. Singh, "Specular Spectroscopic Profilometry for the Sub-0.18 μm PolySi-Gate Process", *Proc. of SPIE, vol. 3998, 2000.*

12. A. C. Diebold, R. K. Goodall, "Interconnect Metrology Roadmap: Status and Future", *Proceedings of the IEEE International Interconnect Technology Conference, 1999, 77-79.*